1UP

NASA TECHNICAL TRANSLATION NASA TT F-14,895

STOL AIRCRAFT WITH MECHANICAL HIGH-LIFT SYSTEMS COMPARED WITH STOL AIRCRAFT WITH WINGS EQUIPPED WITH BLOWN FLAPS

E.-A. Bielefeldt

Translation of STOL-Flugzeuge mit mechanischen Hochauftriebsystemen im Vergleich zu STOL-Flugzeugen mit Blasklappenfluegeln," Messerschmitt-Boelkow-Blohm bmBh, Report UH-12-72 (o),(Paper 72-057 presetned at the fifth annual meeting of the DGLR, October 4-6, 1972,) 20 Sep 72, 35 pages.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 MAY 1973

37

STANDARD TITLE PAGE

1. Report No. NASA TT F-14,895	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STOL AIRCRAFT WITH MECHANICAL HIGH-LIFT SYSTEMS COMPARED WITH STOL AIRCRAFT WITH WINGS EQUIPPED WITH BLOWN FLAPS		5. Report Date May 1973
		6. Performing Organization Code
7. Author(s) E.-A. Bielefeldt		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASw 2481
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of STOL-Flugzeuge mit mechanischen Hochauftriebsystemen im Vergleich zu STOL-Flugzeugen mit Blasklappenfluegeln," Messerschmitt-Boelkow-Blohm bmBh, Report UH-12-72 (o),(Paper 72-057 presetned at the fifth annual meeting of the DGLR, October 4-6, 1972,) 20 Sep 72, 35 pages.

16. Abstract Net lifts of modern mechanical auxiliary high-lift systems and blown flaps are compared, as used on STOL aircraft with high surface loads. The possibilities for achieving aerodynamic efficiencies with these high-lift systems are first discussed. Aerodynamic system problems and the effects of system weights of different auxiliary high-lift devices on net lift are considered. The net lifts of complex mechanical and blown-flap systems are determined as applied to a STOL aircraft configuration based on a surface load of 370 kg/m^2 for which a maximum lift coefficient of about 3.5 is required in the trimmed state. It is found that mechanical high-lift systems are superior to blown flaps in this comparison.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	33	4.00

Symbols and Dimensions

$c_{l\ max}$		Maximum lift coefficient of section profile or profile system (quasi-two-dimensional)
$\Delta c_{l\ max}$		Increase in maximum lift coefficient produced by flap extension
$c_{l\ max\ W/\ WB}$		Maximum lift coefficient with blowoff in wind tunnel side walls and/or end plates
$c_{l\ max\ w/o\ WB}$		Maximum lift coefficient without side wall blowoff
$c_{L\ max}$		Maximum lift coefficient obtainable for the aircraft
$\Delta c_{L\ Tr}$		Trim lift loss
c_{μ}		Augmentation-air momentum coefficient
$c'_{\mu A}$		Momentum coefficient for adjacent flow
Ma_B		Mach number in blowing air duct
q_{∞}	kg/m^2	Dynamic pressure in flight
Λ_{geom}, Λ		Geometric aspect ratio, aspect ratio
A	m^2	Wing area
φ	o	Sweep-back angle
A_E	m^2	Elevator area
V_E	m^3	Elevator volume
l	m	High-speed section profile depth
l_t/l_r		Wing taper
l_{eff}	m	Effective section depth
l_{μ}	m	Reference chord length
x_o	m	Distance of neutral point of entire aircraft behind neutral point of wing-fuselage combination
x_{cg}	m	Distance of center of gravity behind neutral point of wing-fuselage combination
l_F, $l'_{F\ eff}$	m	Effective flap depth
l_{F1}, l_{F2}	m	Component flap depths
η_F	o	Flap angle

D_{Fu}	m	Fuselage diameter
W_T	t, kg	Takeoff weight
$W_{T/A}$	kg/m^2	Surface load
$W_{W\ w/\ F}$	kg	Weight of wing assembly with flaps
$W_{W\ w/o\ F}$	kg	Weight of wing without flaps

STOL AIRCRAFT WITH MECHANICAL HIGH-LIFT SYSTEMS COMPARED WITH STOL AIRCRAFT WITH WINGS EQUIPPED WITH BLOWN FLAPS

E.-A. Bielefeldt

Summary /ii*

In the selection of a special high-lift system for a STOL aircraft project, its aerodynamic properties are not the only factors which are decisive. A consideration of various auxiliary high-lift systems must take the integration of the particular high-lift device into the overall system into consideration. Critical criteria here include not only the maximum lift which can be obtained or moment and resistance behavior, but also system weight, flight characteristics, system reliability and safety, and production costs and proportionate operating costs.

This paper is limited to net-lift comparisons between modern mechanical auxiliary high-lift systems and blown flaps as applied to STOL aircraft with high surface loads. The possibilities for achieving aerodynamic efficiencies with these high-lift systems are first discussed. Aerodynamic system problems and the effects of system weights of different auxiliary high-lift devices on net lift are considered. The net lifts of complex mechanical and blown-flap systems are determined as applied to a STOL aircraft configuration based on a surface load of 370 kg/m^2 for which a maximum lift coefficient of about 3.5 is required in the trimmed state. It is found that mechanical high-lift systems are superior to blown flaps in this comparison.

* Numbers in margin indicate pagination in the foreign text.

1. Introduction

/1

Shortening takeoff and landing distances in the development of modern short-takeoff aircraft with high surface loads requires the application of up-to-date auxiliary high-lift systems to reduce minimum airspeed. Maximum trimmed lift coefficients of about 3.5 come under consideration for planned commercial aircraft in this class. This requirement for maximum lift lies within a range of values which approaches the upper limit of maximum lift coefficients which can be achieved with mechanical auxiliary lift systems. It is therefore reasonable to cover the possibility of a transition to blown-flap systems.

In the selection of a special high-lift system for a short-takeoff aircraft project, its aerodynamic efficiency is not the only factor which is decisive. In a comparison of various auxiliary high-lift systems, it is necessary to consider the integration of the particular high-lift device into the overall system. Critical criteria for evaluation here are not only the maximum achievable lift or moment and resistance behavior, but also system weight, flight characteristics, system safety and reliability, and production costs and proportionate operating costs.

A number of results from comparisons, based on projects, between modern mechanical auxiliary high-lift systems and blown flaps are presented in this paper. These considerations cover the installation of high-lift systems in STOL aircraft and are concerned with the above-mentioned $c_{L\,max}$ design range.

First, a discussion of the aerodynamic properties of up-to-date high-lift systems.

2. The Aerondynamic Properties of Up-To-Date High-Lift Systems /2

A large number of possibilities exist today for the production of high aerodynamic lift. New principles keep being introduced. Depending upon mode of functioning, all of these high-lift principles can generally be classified in two large groups, the mechanical and the "driven" high-lift systems (the abbreviated designation "driven high-lift systems" used here may elicit some criticism).

Mechanical auxiliary high-lift systems produce their lift from airspeed alone. Often also called conventional auxiliary high-lift systems and originally making use of the camber effect alone, they have been developed into complex multi-slot wing systems as lift requirements have risen in the course of time. With their lift-increasing effect resulting from the bilateral influencing of flow by the individual section elements -- if their configuration relative to one another is optimal -- the limiting range of increases in lift which can ever be achieved by mechanical means has probably been reached with the multiple slotted flap systems. Apparently the highest two-dimensional maximum lift coefficient for a multiple-slot wing system has been given as about 5.2 by F. Mavriplis [1]. It was achieved experimentally in a wind tunnel with side wall blowoff to produce largely two-dimensional flow character[1]. The high-lift system was installed on a NACA 6^4A210 basic profile, thickness 10%, and consisted of a double slotted flap, depth 35%, at a flap angle of 37.5°, combined with a Krüger variable-camber slat,

---

1 Unfortunately, the test Reynolds number is not specified in the report cited [1]. According to another article published by the same author [2] on the same theme, a maximum lift coefficient of almost 5.1 was obtained at a Reynolds number of about $2 \cdot 10^6$ with a similar high-lift system on the NACA 65_2-215 profile.

depth 20%, which, by itself, is supposed to yield an increase in $c_{L\ max}$ of about 2.1 relative to the section with a double slotted flap. /3

In a comparison of such maximum lift coefficients, we cannot neglect to consider the test setup used in each case. A number of remarks in this regard: In Mavriplis [1], blowoff in the tunnel side walls and/or in the end plates results in an increase in the maximum lift coefficient by $\Delta c_{l\ max\ w/\ WB} \approx 0.7$ (w/ WB = wall blowoff) for a section with a triple slotted flap[2] relative to a maximum lift of $c_{l\ max\ w/o\ WB} = 3.5$ (w/o WB = without wall blowoff) obtainable with the same section configuration without wall blowoff. On the other hand, van den Berg [3] gives an increase in lift of about 0.3 for the effect of wall blowoff, relative to a $c_{l\ max}$ value of approximately 3.21 without wall blowoff. Both studies are based on geometric aspect ratios of $\Lambda_{geom} = 1.5$ and 3.5 for the models between the wind tunnel walls. Thus the effect of wall blowoff increases with decreasing aspect ratio, as to be expected. We can assume that for very small side wall distances (or end plate distances), appreciable lift coefficients are not obtained unless there is simultaneous blowoff in the side walls. If we take the fact that this effect must disappear for very large model lengths into consideration, on the other hand, the influence of wall blowoff can be illustrated with the above-cited data as shown in Fig. 1. Curve regions of hyperbolic character are obtained in each case for constant $c_{l\ max}$ values and various high-lift systems. The region of scatter drawn in must result from the fact that trailing-edge flap systems differing in the number of section elements (double slotted and triple slotted flaps) were associated with it. Since only the data cited was available for the above discussion,

---

2 NACA 4417 basic profile, total flap depth 35% of high-speed profile depth.

it was only possible to indicate the trend in the dependence of wall blowoff effect upon $c_{l\,max}$ to be expected, by means of arrows.

This pronounced effect of wall blowoff on the quality of the two-dimensional flow character of high-lift measurements is mentioned because it is usual, for various reasons, to compare the aerodynamic efficiencies of different high-lift systems or the effect of parameter variations on a single high-lift system for planar flow around it. To briefly mention a few reasons: limitation of measurement parameters, particularly in the case of multiparameter high-lift systems, such as triple slotted flaps combined with slats; the easier production and handling of cylindrical models; and higher possible Reynolds numbers in a given wind tunnel. /4

It thus appears explainable that the majority of all high-lift measurements known to date have been carried out for quasi-two-dimensional flow about the high-lift section systems. Since these results have almost all been obtained without affecting wall boundary layers, a comparative analysis of various model measurements involving the pronounced three-dimensional effect of boundaries on the sides appears to be questionable even for approximately equivalent Reynolds numbers and degrees of flow turbulence.

A comparison of a large number of quasi-two-dimensional measurement results can therefore only be of qualitative significance. In Fig. 2, measured $\Delta c_{l\,max}$ values for various auxiliary high-lift systems such as plain flaps, split flaps, single, double and triple flaps [1, 4-7] are plotted against the product of flap angle η_F and the square root of relative flap depth $\sqrt{l_F/l}$. Derivation of the increase in lift resulting from flap extension on the basis of potential theory as described by Glauert [5, 8] indicates that, as a first approximation, it is proportional to the product $\eta_F\sqrt{l_F/l}$. An attempt has been made to determine the aerodynamic efficiency of multiple cambers and the Fowler effect by taking effective relative flap depths or component flap depths into consideration with component flap angle by summing $\Sigma\eta_F\sqrt{l_F/l}$ in evaluating the given data in each case. The measured maximum increase in lift resulting from flap extension, $\Delta c_{L\ max}$, and the expression $\Sigma\eta_F\sqrt{l_F/l}$ can then be conceived of as differentiating parameters for a sort of aerodynamic efficiency comparison between various high-lift systems. The effect of the number of flap slots was clearly manifested in the slotted wing systems. As the number of slots is increased, the transition to double slotted flap and triple slotted flap systems permits larger and larger flap angles to be achieved with constant total flap depth or greater and greater flap depths, with a lift-enhancing effect, to be achieved with a constant final flap angle, until an indicated optimal value for $\Sigma\eta_F\sqrt{l_F/l}$ is reached. /5

In view of the large number of different statistically evaluated experimental results, we could venture an attempt to specify limiting aerodynamic efficiencies for mechanical high-lift systems by means of an envelope. The common envelope drawn in in Fig. 2 for the three different slotted wing systems suggests that aerodynamic efficiency $\Delta c_{l\ max}$ can hardly be expected to be further enhanced with the addition of a fourth flap slot.

Due to the small number of measurement results available on triple-slot landing flaps, limiting efficiency could only be extrapolated for this complex high-lift system. The two lone data points plotted [7] lie below this slightly extrapolated limiting efficiency and are still in the double slotted flap region, i.e., these measurement results could not be based on optimum flap angles for the large effective flap depths, $l_{F\ eff}/l = 0.45$.

The shortage of data on triple-slot auxiliary high-lift systems might be explained, on the one hand, by the fact that this mechanical high-lift system was relatively new and has so far been installed on only a few modern commercial aircraft belonging to one aircraft producer, Boeing. Because develop- /6 ment of this high-lift system for the first time, for the Boeing 727 airliner, represented the most expensive single development project within the overall program for this aircraft model [9], it is understandable that test reports by the developing firm are not very accessible, if at all. On the other hand, the complexity of triple-slot landing flaps, particularly with respect to the multiparameter nature of the system, may have been the reason why there are still no systematic studies available today on this subject from aeronautical institutes.

In view of the maximum lift requirement of $c_{L\ max} \approx 3.5$ in the fully trimmed state mentioned above for first-generation commercial STOL aircraft, we can probably expect that such aircraft, when equipped with mechanical auxiliary high-lift systems, will have highly develped multiple slotted landing flaps, not necessarily triple slotted flaps, combined with effective auxiliary leading-edge devices such as relatively deep slats or Krüger slats.

A number of aerodynamic aspects of the development of such high-lift systems will be discussed briefly below:

For the majority of all double slotted landing flaps studied to date, the first flap element (or flap slat) has a very much smaller depth l_{F1} than the second flap section (or main flap), with depth l_{F2}, i.e. two flap slots follow one another at a short distance. The aerodynamic necessity of this becomes understandable if we consider the extension path for such flap systems. In the case of these double slotted flaps with very small l_{F1}/l_{F2} ratios, the flap slat is usually designed to be fixed relative to the main flap, and when extended, the entire flap rotates about a pivot located near the underside of the wing. In this way it is possible to use relatively light flap extension mechanisms. The short distance between the two flap slots then results from the requirement for relatively /7 pronounced flow deflection over a short path. This type of double slotted flap is illustrated in Fig. 3, top. Various experimental results from wind tunnel studies and recent theoretical considerations by A. M. C. Smith regarding the slot effect in multiple-slot wings [10] indicate, however, that higher aerodynamic efficiencies can be achieved if the depths of the individual section elements strung together in the multiple slotted flap decrease, as viewed in the direction of flow, and only a rather small partial deflection relative to the total deflection occurs at each flap slot (Fig. 3, center). Only in this way can large ultimate flap angles be achieved by means of several partial flap angles. These partial flap angles can be achieved by moving the individual flap elements relative to one another during extension. This is connected with a simultaneous increase in effective flap depth $l_{F\ eff}$. The maximum lift increases which can be achieved with an enhanced Fowler effect combined with increased flap depth can be so great for well-profiled flap systems that they need not be utilized to full extent for certain aircraft projects. This then offers the possibility of a transition to smaller flap angles and other slot configurations, deviating from those for best maximum lift. Thus a certain amount of tolerance exists for the selection of favorable fineness ratios in the range of large flap angles, which may have an advantageous effect, for example, on the touch-and-go capability of an aircraft attempting to land particularly in the case of powerplant failure. The aerodynamically favorable design of such multiple-slot flap systems with a high Fowler effect and large effective flap depth relative to flap depth in the retracted state is accompanied, however, by a considerable increase in weight relative to the above-mentioned simple extension mechanisms (this will be covered in greater detail in the discussion of weight).

Most of the Fowler effect -- if by this we mean the enlargement of area -- is produced by relative movement of the first flap element with respect to the trailing edge of the main wing (on the fixed wing component) and that between the first and second flap elements, if adequate wing thickness permits /8 relatively extensive overlapping of the individual section elements in the retracted state. Likewise, most of the increase in effective flap depth can be achieved through relative movement between the first and second flap elements. For a relatively small flap depth and small trailing-edge angle in the high-speed section profile, a third flap slot will therefore contribute little to increasing effective flap depth and, due to the large extension angle of the rear flap element, will hardly contribute to the Fowler effect. This then explains why comparative measurements carried out by J. Amtsbert [7] yielded a lift loss of only $\Delta c_{l\ max} \approx 0.13$ relative to a maximum lift coefficient of 3.54 (triple slotted flap) if a split flap of the same depth was used on the second flap element in place of the third section element on a triple slot landing flap. Both flap systems, i.e. the triple slot flap and the double slot flap with auxiliary slotted flap, were derived from a pure double slot flap optimized in the wind tunnel, i.e., the section contours of the section systems which were compared, including settings and extension angles of the flap elements, deviated from the initial section system only in the rear section, over about 11% of the high-speed section depth. The double slot flap with split flap exhibited a moment coefficient which was improved by about 14% relative to the triple slotted flap produced in the above manner, with a zero-lift moment coefficient of $c_{mo} \approx -1.13$. When these two flap systems are installed on a trimmed comparison aircraft with full-span flaps, on a straight wing with an aspect ratio of 8, it can be expected that the above-described difference of 0.13 in maximum lift is reduced to an effective lift loss of about 0.04 in quasi-planar flow. This results, on the one hand, from the more favorable installed weight of the auxiliary split flap, but to a much greater degree from its more favorable moment characteristic.

Measurement data shown in Fig. 4 for quasi-planar flow [11] indicate similarly advantageous effects of an auxiliary split flap combined with slotted-wing systems. In this test project by the firm of MBB, the efficiency of an auxiliary split /9 flap, depth 10%, on a Fowler flap, depth 30%, with aerodynamically favorable upstream profiling was studied, among other things. Slot settings and all flap extension angles were optimized relative to $c_{l\ max}$, both with and without the auxiliary split flap, at a Reynolds number of $1.2 \cdot 10^6$ [3] in the DFVLR wind tunnel at Porz-Wahn. A zero-lift moment coefficient of $c_{mo} \approx -0.77$ was obtained with the pure Fowler flap. The moment coefficient could be improved by almost 21%, to -0.61, by adding the auxiliary split flap, while the maximum lift coefficient was increased by 0.1, to 2.7.

---

[3] A system of turbulence vanes was used in these tests with which an effective Reynolds number of $Re_{eff} \approx 3 \cdot 10^6$ was obtained.

B

Although only a small number of measurement data are known, it can be seen from the recent projects referred to above that split flaps combined with slotted-flap systems are a simple mechanical aid for improving the aerodynamic properties of slotted wings. The following advantages are offered:

a) More favorable installed weight, simpler structure and simpler mechanics if the problem is whether an auxiliary split flap should be used in place of an additional flap slot, i.e. the addition of another flap section.

b) A favorable effect on the moment characteristic, with a considerable reduction in trim lift losses.

c) A lift-enhancing effect which should be even further improved when greater auxiliary split flap depths are used.

The effective generation of lift by means of multiple-slot wings results in complex mechanical systems. They are characterized by a large number of parts and complicated movements of individual flap elements relative to one another over long extension paths. But plain flaps with augmentation are outstanding among driven auxiliary high-lift systems, considered in terms of the landing flap itself, due to their mechanical simplicity. This special group of auxiliary high-lift systems makes use of the possibility of affecting flow /10
over the camber face of the wing with the aid of a pressure reservoir with a higher total pressure level than that associated with the velocity of approaching flow. An additional increase in lift, over and above its mechanical lift component, is therefore achievable -- as is well known -- with such flap systems. This increase is based, to a relatively small extent, upon "jet reaction," and to a larger extent, particularly in a favorable

flap design, on the induction effect of the augmentation jet. The latter component is also called circulation lift. The reference parameter for the aerodynamic efficiency of driven high-lift systems is augmentation momentum coefficient c_μ. This is obtained from the quotient of augmentation thrust required to affect flow divided by the product of dynamic pressure in flight times loaded wing area. The ratio of lift to augmentation momentum coefficient, c_L/c_μ, is a measured of the aerodynamic quality of the particular high-lift system. Fig. 5 shows how much the characteristics c_L vs. c_μ depend upon the type of system. The efficiency of the pure jet flap, relatively low for driven auxiliary high-lift systems (Curve 1), can be considerably improved by combining the augmentation jet with a mechanical auxiliary lift system such as a plain flap. In order to also demonstrate the effect of an unfavorable location of the augmentation slot in this comparison, the characteristic for a plain flap with trailing-edge augmentation is included in Fig. 5 (Curve 2). Due to the higher mechanical enhancement of lift resulting from extension of the plain flap, a considerable improvement in aerodynamic effectiveness is obtained relative to the pure jet flap, particularly for low c_μ values, but it falls off rapidly with higher augmentation momentum for a more and more prominent jet-reaction component.

Shifting the single outlet point to the most favorable location for this high-lift system, just in front of the pressure minimum at the "knee" of the flap, results in an additional improvement in lift, approximately in the form of a parallel shift in the curve for trailing-edge augmentation plain flaps /11
(Curve 3). This enhancement of lift due to the parallel shift in the lift characteristic increases with increasing flap angle (Curve 4) until, at even greater flap angles -- an example for 90^o is shown -- an increase in lift caused by increasing flap

angle can only be achieved with very high values for augmentation momentum coefficient (Curve 5). The breakdown in lift relative to the smaller flap angles of 60° and 45° in the region of lower c_{μ} values is explained by the fact that the jet can only follow the deflection arc at the knee of the flap -- which has become too long -- for only a very short distance and, separated, prematurely continues on its path at a farther distance from the camber face of the flap, much as in the case of the pure jet flap. Expressed differently: The flatter rise in the curve results from the injection of a free jet into considerable "dead water." The energy of the jet is utilized, to a large extent, only to generate reaction lift until supercirculation is brought into play.

Aerodynamic efficiency limits for this simple blown-flap system, driven flap with augmentation at the flap "knee," are probably reached with Curves 3, 4 and 5 as shown in Fig. 5. Variation of flap depth makes it possible to achieve further increases in lift, as in the case of pure mechanical flaps, in accordance with the proportionality between c_l and $\sqrt{l_F/l}$ for constant c_{μ}, as does the changing of high-speed section geometry and flap geometry. Thus just an increase in the relative nose radius of a plain flap behind its augmentation slot produces an improvement in lift of $\Delta c_l \approx 0.15$ in the c_{μ} range for supercirculation, according to measurements by G. Streit and F. Thomas [14]. Nose radius was increased by shifting the flap pivot from the section midline to the underside of the high-speed section profile, from 3.8% to 7.5% of section depth[4].

---

[4] NACA 63_2A218 high-speed section. All flaps: $l_F/l = 0.222$; $\eta_F = 60^{\circ}$; $\alpha = 0^{\circ}$.

If the mechanical simplicity of the augmented plain flap is to be retained, the possibilities mentioned above for improving aerodynamic efficiency are limited. If flow is sharply deflected by the plain flap, it is necessary to accept the need for relatively high drive performance for affecting flow. /12

Much greater increases in lift can be achieved with relatively low values for augmentation momentum coefficient if we go to mechanically more complex systems with gradual flow deflection and multiple influencing of flow. Combining suction and augmentation via ejectors results in extraordinarily high c_l/c_μ values in the range of small augmentation momentum coefficients (Curves 6 and 7). To date, the highest-performance auxiliary high-lift system is probably the ONERA Poisson-Quinton double flap (Curve 7).

Of the large number of various principles for generating high lift, a few possibilities have been described here for producing high lift coefficients by purely mechanical means and with blown flap systems. As was mentioned above, the usual approach is to initially compare aerodynamic efficiencies in quasi-planar flow if the problem is to equip wings with relatively high aspect ratios with suitable auxiliary high-lift systems for a particular lift requirement.

In the transition to wings of finite aspect ratio with a wide variety of sources of disturbance and three-dimensional flow effects, reductions occur in the two-dimensional high lift coefficients which will be referred to collectively as aerodynamic installation losses.

3. Effects of Aerodynamic Installation Losses with High-Lift Wings /13

The aerodynamic installation losses of an aircraft configuration under consideration are codeterminant in the preselection of special high-lift systems, or can even effect the selected configuration itself. The requirement of a specific maximum trimmed lift coefficient for a STOL aircraft project results in much higher lift coefficients for planar flow, due to the total accumulation of installation losses. Unfortunately, only a very small number of data, often inadequate, are available for estimating the various effects. Systematic wind-tunnel tests for preliminary-project studies become very expensive for the aircraft configurations which come under consideration, usually several in number, due to the increase in the number of study parameters which results. In such preliminary studies, it is often therefore necessary to put up with greater imprecision in the experimental results if only statistically determined estimates of reduction effects can be made.

With this reservation, aerodynamic installation losses were determined for a STOL aircraft configuration as described by D. Fiecke [15] with the following design data:

Takeoff weight	W_T	= 80 t
Surface load	W_T/A	= 370 kg/m^2
Aspect ratio	Λ	= 8
Wing taper	l_t/l_r	= 0.4
Sweep-back angle	φ	= 0°
Fuselage diameter	D_{Fu}	= 4.80 m

Full-span multiple slotted flaps and partial-span flaps over 4/5 span, with slats; 4 jet powerplant nacelles on the wing.

Only about 80% utilization of the quasi-two-dimensional maximum lift coefficient is obtained for the unswept pointed wings with landing flaps extending over the full span. With a trim lift loss of about $\Delta c_{L\ Tr} = 0.34$, this would result in a $c_{l\ max}$ value of approximately 4.8 in planar flow if a trimmed maximum lift coefficient of 3.5 is required for the aircraft. This means that effective multiple slotted flaps would have to be installed very carefully in combination with slats. /14

In a transition to partial-span landing flaps, extending over 4/5 of total span, only about 72% of the maximum lift which can be achieved two-dimensionally would still be usable. This would already make an increase in the quasi-two-dimensional maximum lift value to about 5.3 necessary for the same trimmed maximum lift requirement for the aircraft.

Such lift coefficients cannot be achieved with mechanical auxiliary high-lift systems for swept-back wings with relatively large sweep angles.

Larger aircraft rotation angles become necessary for STOL aircraft takeoff. Studies performed by the firm of MBB have shown that a transition to shorter and thicker fuselages becomes necessary for this purpose. As fuselage diameter increases, however, installation losses caused by the influence of the fuselage increase.

Relatively pronounced decreases in lift also result from the greater powerplant nacelle diameters to be expected. A special problem is represented here by locally induced flow fields from powerplant intakes and powerplant jets if they are located near flap slots in mechanical auxiliary high-lift systems. The effect can have a favorable or unfavorable local influence on flow around slotted wings, depending on the arrangement of powerplant nacelles relative to the multiple slotted flaps. In any case, the pronounced alteration of the flow field by the powerplant jets in the span direction should be unfavorable, since it is not possible to set up optimum slot geometries and flap angles at every profile section. This difficulty is eliminated if blown flaps are used.

In the complex multiple slotted flap systems described below, /15 flap mounts and their fairings can have considerable dimensions. The disturbances in slot flows which result can be reduced if the extension mechanisms are installed in stagnation flow regions in front of the thrust face of the flap.

Additional lift losses are produced by turbulence formation and flow separation at flap boundaries, at interruptions and recesses in flap sections.

The exact determination of aerodynamic installation losses requires tests on complete models. Extensive wind-tunnel studies become necessary in order to keep these unavoidable flow losses low to satisfy a high lift requirement.

In addition to lift reduction resulting from the aircraft configuration, the obtainable $c_{L\ max}$ value is affected to a considerable extent by trim lift losses. These differ widely with the various high-lift systems. Appreciable reductions in noseheavy moments which must be trimmed can be achieved by favorable combinations of auxiliary leading- and trailing-edge systems. Fig. 6 shows an example of this.

The aerodynamic quality of a high-lift system is not the only decisive factor in its selection for a specific aircraft project, however. Another evaluation criterion is installation weight.

Effects by various high-lift systems and design parameters on installation weights will be discussed briefly below.

4. Weight Comparisons Between Various High-Lift Systems /16

In order to calculate the weights of airfoils with the various high-lift systems, a computing method used by the firm of MBB was employed which was augmented with statistical data to take parameter variations associated with the auxiliary high-lift systems into consideration. It was necessary to accept relatively large uncertainties in weight determination here for extreme high-lift system configurations with very large flap depths and extension distances[5].

The effect of c_μ for blown flaps upon pure landing flap weight, with flap mounts, was determined on the basis of an equivalent design velocity obtained via the c_μ-dependent increase in lift.

In the determination of weight required for blowing-air ducts and additional powerplant weights for producing compressor bleed air, the following approach was used to obtain a given c_μ value:

The cross-section requirement per unit throughput for constant Mach number $Ma_T = 0.3$ in the pipe was first determined as a function of powerplant-related combinations of static conditions p_o (static pressure) and T_o (static temperature) for the blowing air. From this, the weight outlays per unit pipe length and unit throughput were determined via the familiar

---

[5] In the case of extreme flap depth, the parameters frequently fell quite far outside known statistical ranges.

boiler formula. The values of blowing power per unit throughput or specific blowing momentum were calculated at the same time. Rolls Royce turbo-fan power plants currently under development were installed for obtaining blowing air, combined for pre-established c_μ values or blowing momenta $c_\mu q_\infty A$ so that required augmentation momentum, including that from pipeline losses, was about equal to installed potential pneumatic thrust. Minimum added power plant weights were obtained this way on the basis of residual propulsive thrust for known thrust/weight /17 ratios without the use of bleed air. Malfunction safety devices, weights for valves, elbows, deflectors and blowing-nozzle reinforcement were taken into consideration as a whole by making calculations with constant pipeline diameters and allowing about 30% of pipe weight for them. Pipes which are reduced in size are then included in the computations with 70% pipe weight.

The effect upon wing system weight produced by various mechanical high-lift systems and pure flap weights (without blowing air ducts and additional powerplant weights) of blown plain flaps are shown as functions of flap depth ratio l_F/l. All wing system weights with flaps, $W_{W\ w/\ F}$ have been referred to the weight of the wing without flaps, $W_{W\ w/o\ F}$. The ratio $W_{W\ w/\ F}/W_{W\ w/o\ F}$ is independent of surface load W_T/A and of the sweep-back angle of the wing. The highest system weights are produced by triple slotted flaps combined with leading-edge devices. They also exhibit the greatest dependence upon flap-depth ratio. For an equivalent measurement ratio of 40% of high-speed section depth -- a rear spar position of about 55% was assumed for this -- an increase of almost 50% in wing weight is obtained with flaps relative to the wing without flaps.

The pure blown-flap weights, without the weights of air ducts and additional powerplant weight for producing blowing air, depend on augmentation momentum coefficient c_μ, since flap load varies with c_μ. At the momentum coefficient for adjacent flow, i.e. $c_\mu/c_{\mu A} = 1$, their installed weights lie between those of plain double slotted flaps with fixed flap slats and those with moving flap slats.

In a net lift comparison between wings with multiple slotted flaps and blown flaps, it is necessary to take the total installed weight of the blown flap systems and trim lift losses into consideration.

5. Net Lift Comparison Between Mechanical Flap Systems and Blown Flaps /18

Net lift for two mechanical and two blown flap systems, with the flaps extending the full span, were estimated on the basis of various wind tunnel results, using the starting data given in Section 3 for an STOL aircraft configuration. Additional data for determining trim lift losses are given in the upper right of Fig. 8. The compared high-lift systems included the following types of flaps:

(1) A Fowler flap, 30% depth, with an auxiliary split flap, 10% depth, based on an MBB design [11]. The flap has a 100% Fowler effect, i.e., when it is extended, it is moved to the trailing edge of the NACA 64-210 high-speed section profile (10% thickness) -- this explains the relatively high effect of installed weight, expressed in $\Delta c_{L\ max}$. In order to give the landing flap a suitable camber-face profile, it was equipped with an auxiliary leading-edge flap designed in such a manner that a portion of the contour of the NACA 23018 section could be maintained from the leading edge of the flap well toward the trailing edge (see also Fig. 4). This Fowler flap was combined with a suitably profiled wing slat, depth 20%, with a nose flap, on the main wing. The low trim lift losses can be atributed

to the favorable effect of the auxiliary split flap mentioned above and to the high slat efficiency.

This detailed description of the flap data has been provided in order to show that it is possible to achieve high aerodynamic efficiency for a mechanical high-lift system with very high net lift, even with a small number of elements, when all elements of a slotted wing system with leading-edge and trailing-edge flaps are favorably profiled.

System (2) is a triple slotted flap [7], as mentioned above, with an effective total flap depth of 45%. A flap system was likewise combined with a slat. The effect of the slat upon aerodynamic efficiency is estimated. /19

In case (3), net lifts are estimated for the ONERA double flap with a total flap depth of 27.5%. The aerodynamic data apply to a combination of trailing-edge flap and nose flap [16].

In case (4), net lifts have been estimated for a single blown plain flap, depth 25.7% [13], combined with a nose flap.

Regions b and c, with broad hatching, represent the c_μ-dependent effects of the pure flap weights (region b) and installed augmentation system weights (region c) for the two blown-flap systems.

The relatively high trim lift losses in the case of the blown flaps can be attributed to the high gross lifts, represented by the upper curves in the finely hatched region a.

The study shows that for a maximum lift requirement in the trimmed state of $c_{L\ max\ Tr} = 3.5$ to 3.6, even higher net lifts can be expected with mechanical auxiliary high-lift systems, as the auxiliary lines drawn in in Fig. 8 show.

The blown-flap systems prove to be superior for higher lift requirements.

6. Closing Remarks /20

It can be said, in summary, that when STOL aircraft are equipped with mechanical auxiliary high-lift systems, higher net lifts can be expected, until the limiting aerodynamic efficiency of complex slotted-wing systems has been reached, than with blown flaps for equal trimmed maximum lift coefficients. If powerplant failure is taken into consideration, the net lift comparison shown in Fig. 8 comes out even more unfavorable for blown-flap systems, since the installed weight of the blowing system is further increased here. In Fig. 8, additional powerplant weights for just the production of the c_L-dependent c_μ value have been taken into consideration, without malfunction reserves for blowing momentum.

Moreover, no considerations have been given in these studies to the effects of controlability requirements, particularly in case of powerplant failure, upon net lift, nor upon the selection of a suitable high-lift system for a specific aircraft configuration. Due to the complex three-dimensional flow conditions, and for the sake of evidence for stability, wind tunnel tests on complete models are essential for such studies.

Finally, the selection of a high-lift system can also be affected by requirements in construction regulations which, for example, necessitate taking larger angles of sideslip resulting from the effect of side winds into consideration. In this case, we can expect blown-flap wings to behave more favorably than wings with multiple slotted flaps.

In addition to safety and reliability requirements, it is also necessary to take manufacturing costs and proportionate operating costs into consideration.

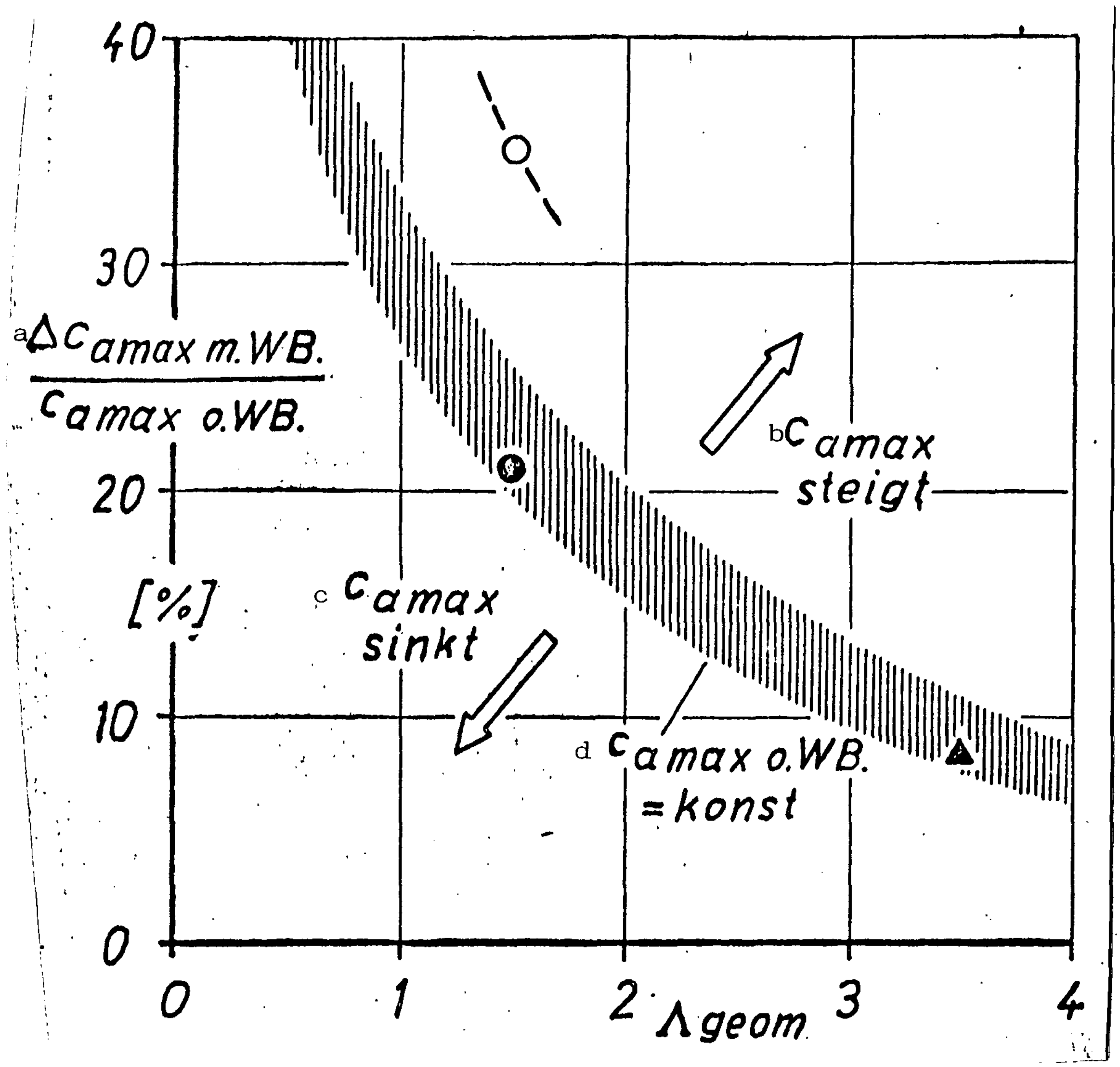

Fig. 1. Estimating the effect of side-wall blowoff upon quasi-two-dimensional high-lift measurement data.

▲ Double slotted flap as described in [3]
$c_{1\ max\ w/o\ WB} = 3.21$ $c_{1\ max\ w/\ WB} = 3.48$

● Triple slotted flap as described in [1]
$c_{1\ max\ w/o\ WB} = 3.52$ $c_{1\ max\ w/\ WB} = 4.25$

o Slat and triple slotted flap as described in [1]
$c_{1\ max\ w/o\ WB} = 3.46$ $c_{1\ max\ w/\ WB} = 4.69$

Key: a. $\Delta c_{1\ max\ w/\ WB}/c_{1\ max\ w/o\ WB}$; b. $c_{1\ max}$ increases; c. $c_{1\ max}$ decreases; d. $c_{1\ max\ w/o\ WB}$ = constant

C

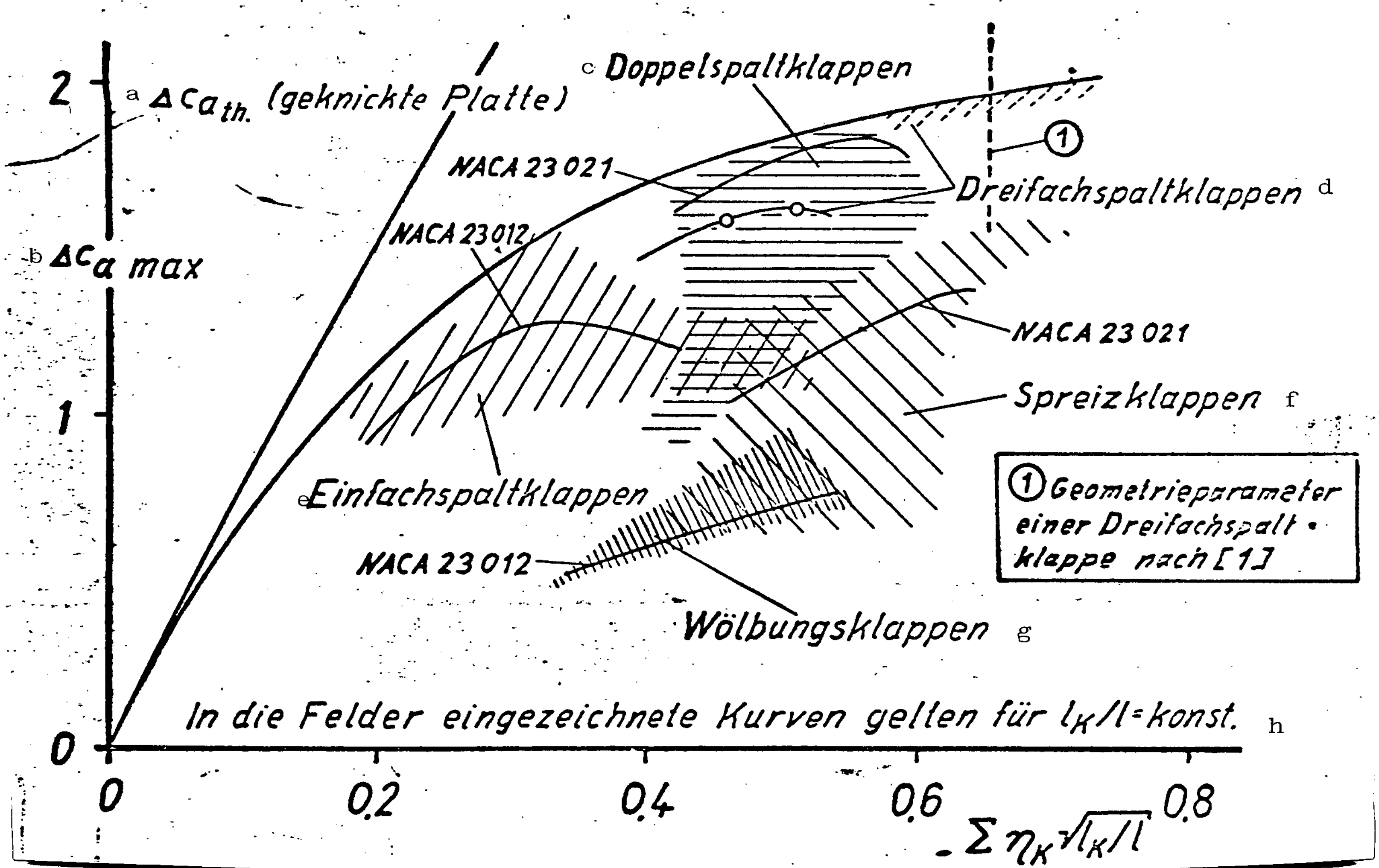

Fig. 2. Comparison of quasi-two-dimensional measurement data on various mechanical high-lift systems.

Key: (1) Geometry parameter for a triple slotted flap as described in [1]; a. Δc_{1th} (bent plate); b. $\Delta c_{1\ max}$; c. Double slotted flaps; d. Triple slotted flaps; e. Single slotted flaps; f. Split flaps; g. Plain flaps; h. Curves drawn in the fields applied to $1_F/1$ = const.

[Note: commas in numerals are equivalent to decimal points]

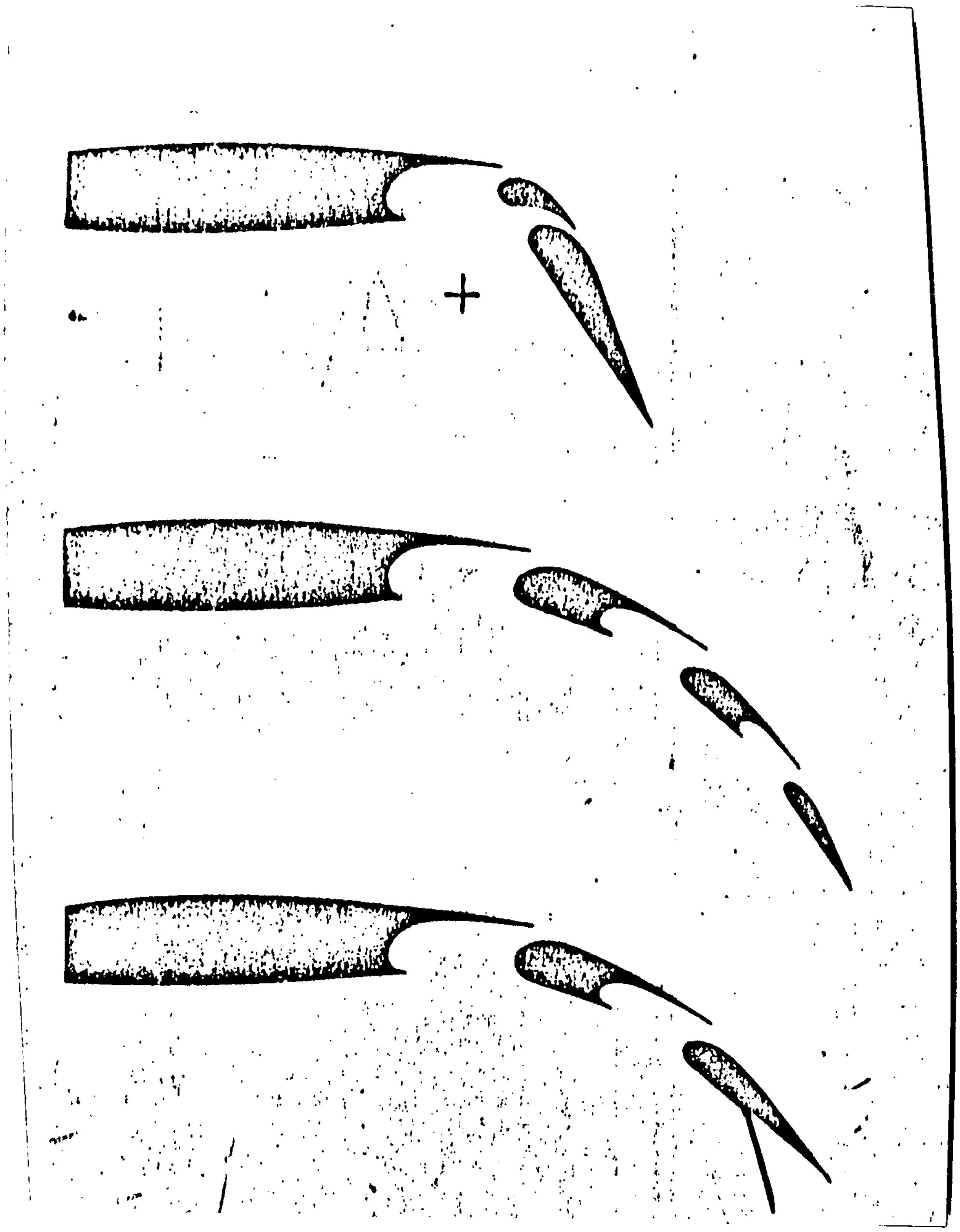

Fig. 3. Various multiple slotted flap systems

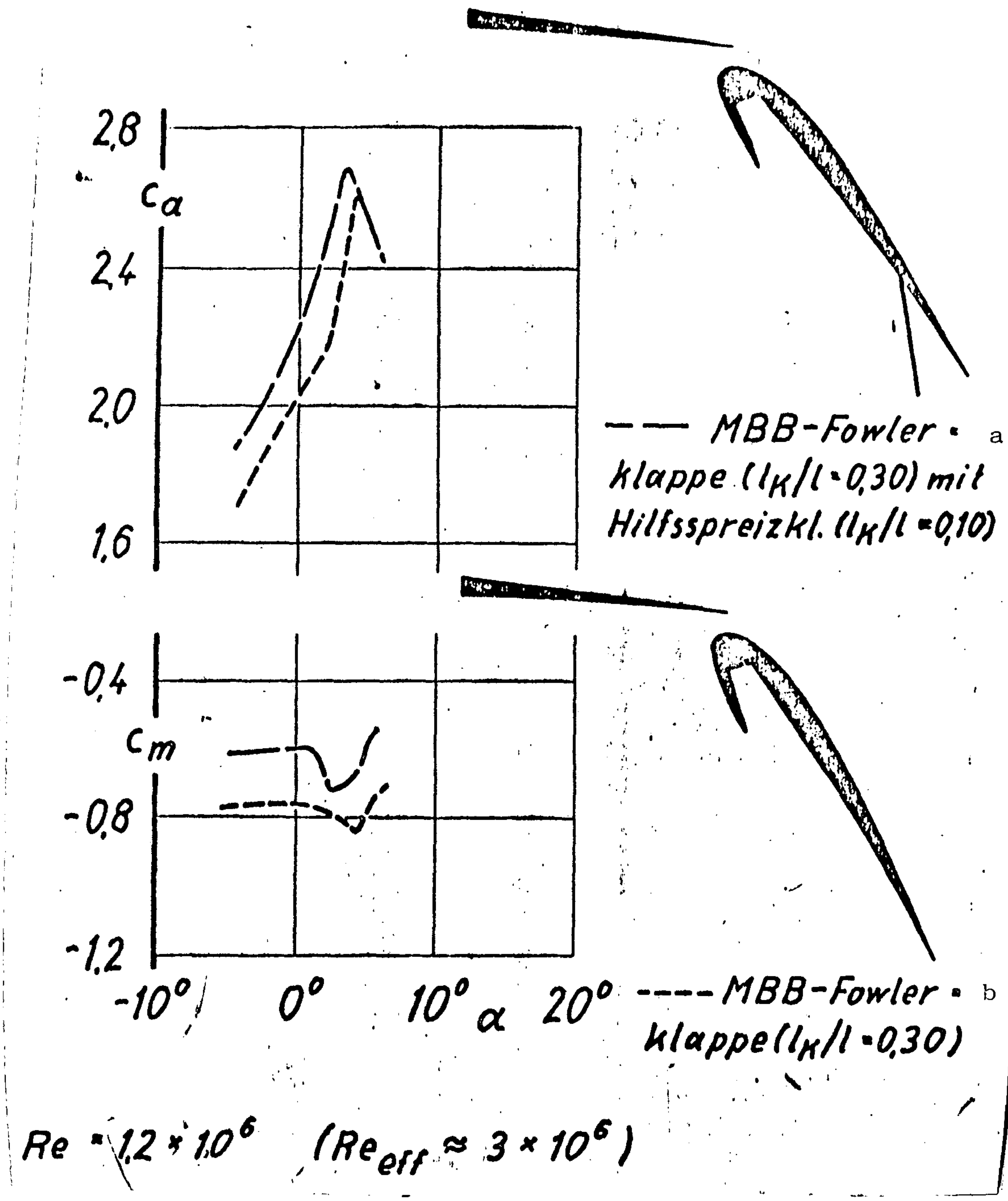

Fig. 4. Effect of an auxiliary split flap on the moment and lift coefficients [11].

Key: a. MBB Fowler flap (l_F/l = 0.30) with auxiliary split flap (l_F/l = 0.10);
b. Fowler flap (l_F/l = 0.30)
$c_a = c_l$

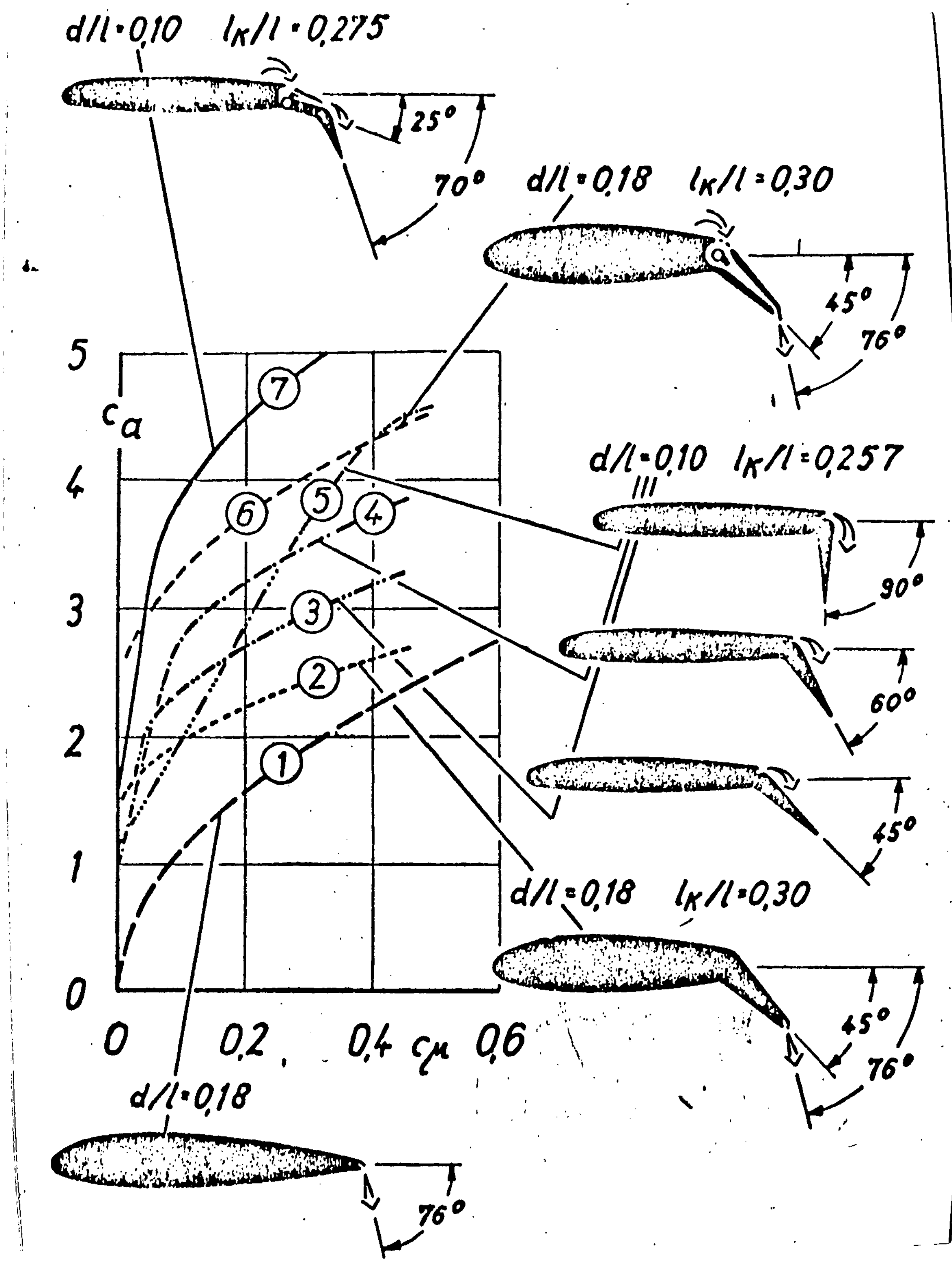

Fig. 5. Lift characteristics c_l vs. c_μ for various driven auxiliary high-lift systems as described in [12, 13]

Key: $l_K = l_F$; $c_a = c_l$

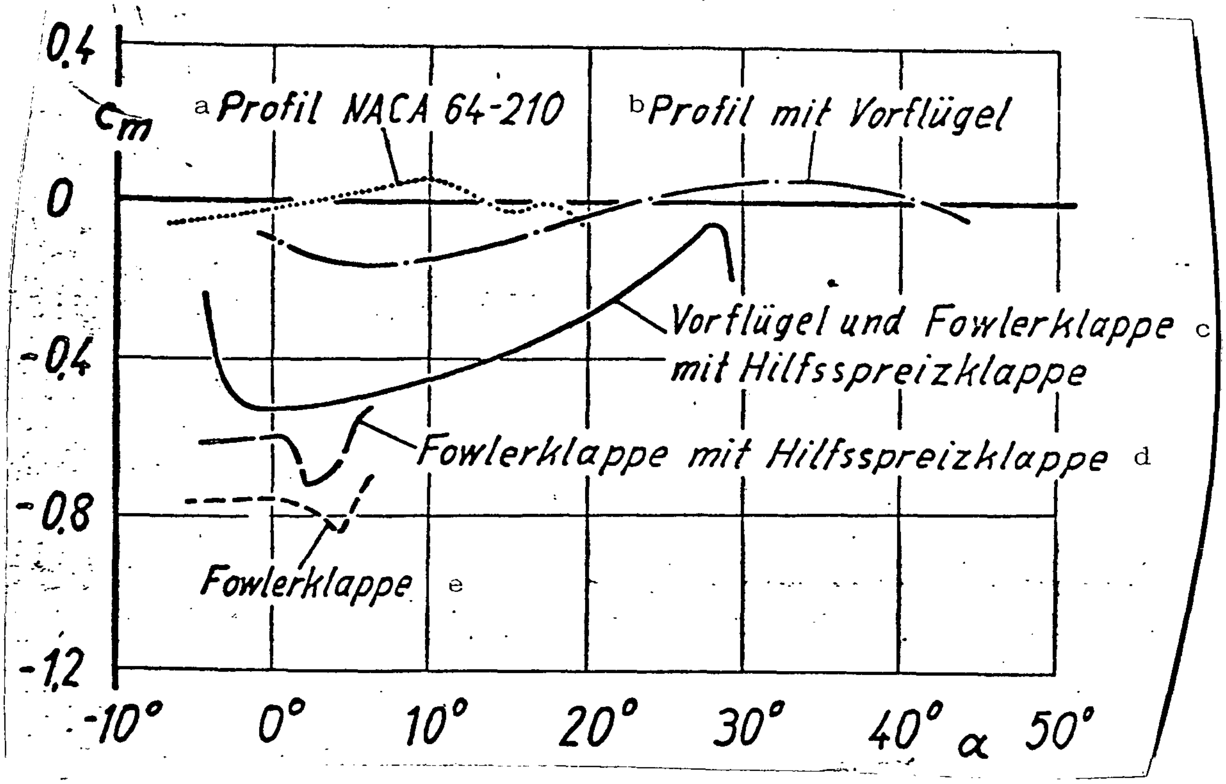

Fig 6. Effect on moment coefficient produced by auxiliary trailing-edge high-lift systems and their combination with slats. MBB design [11].

Key:
- a. Section
- b. Section with slat
- c. Slat and Fowler flap with auxiliary split flap
- d. Fowler flap with auxiliary split flap
- e. Fowler flap

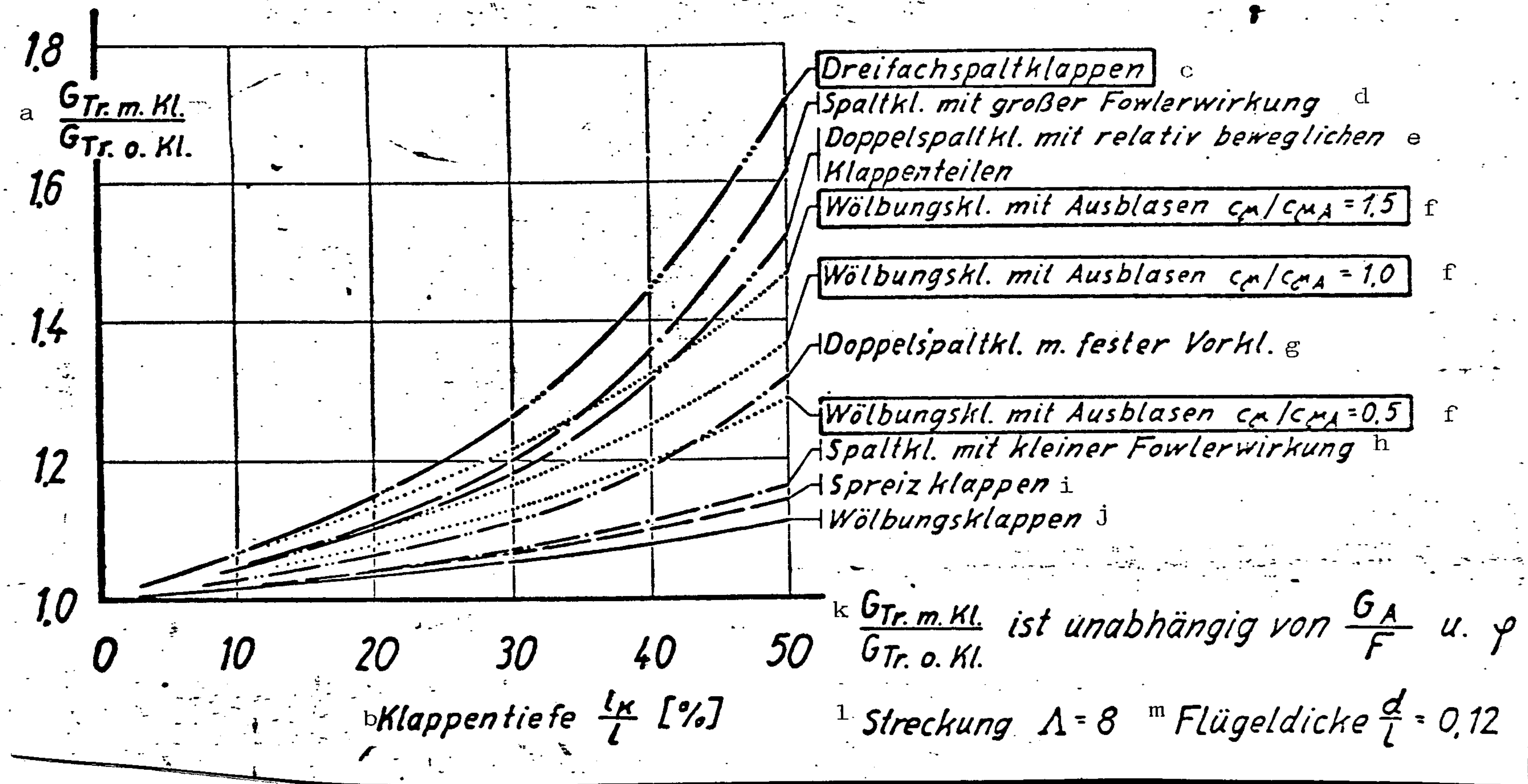

Fig. 7. Comparison of wing assembly weights with various trailing-edge flap systems, combined in each case with auxiliary nose lift systems, depth 15%, as referred to wing weight without flaps.

Key: a. $W_{W\ w/\ F}/W_{W\ w/o\ F}$; b. Flap depth l_F/l; c. Triple slotted flaps; d. Slotted flaps, large Fowler effect; e. Double slotted flaps, relative movement of flap elements; f. plain flaps, augmentation; g. Double slotted flaps with fixed flap slats; h. Slotted flaps with small Fowler effect; i. Slotted flaps; j. Plain flaps; k. $W_{W\ w/\ F}/W_{W\ w/o\ F}$ is independent of W_T/A and φ; l. Aspect ratio; m. Wing thickness

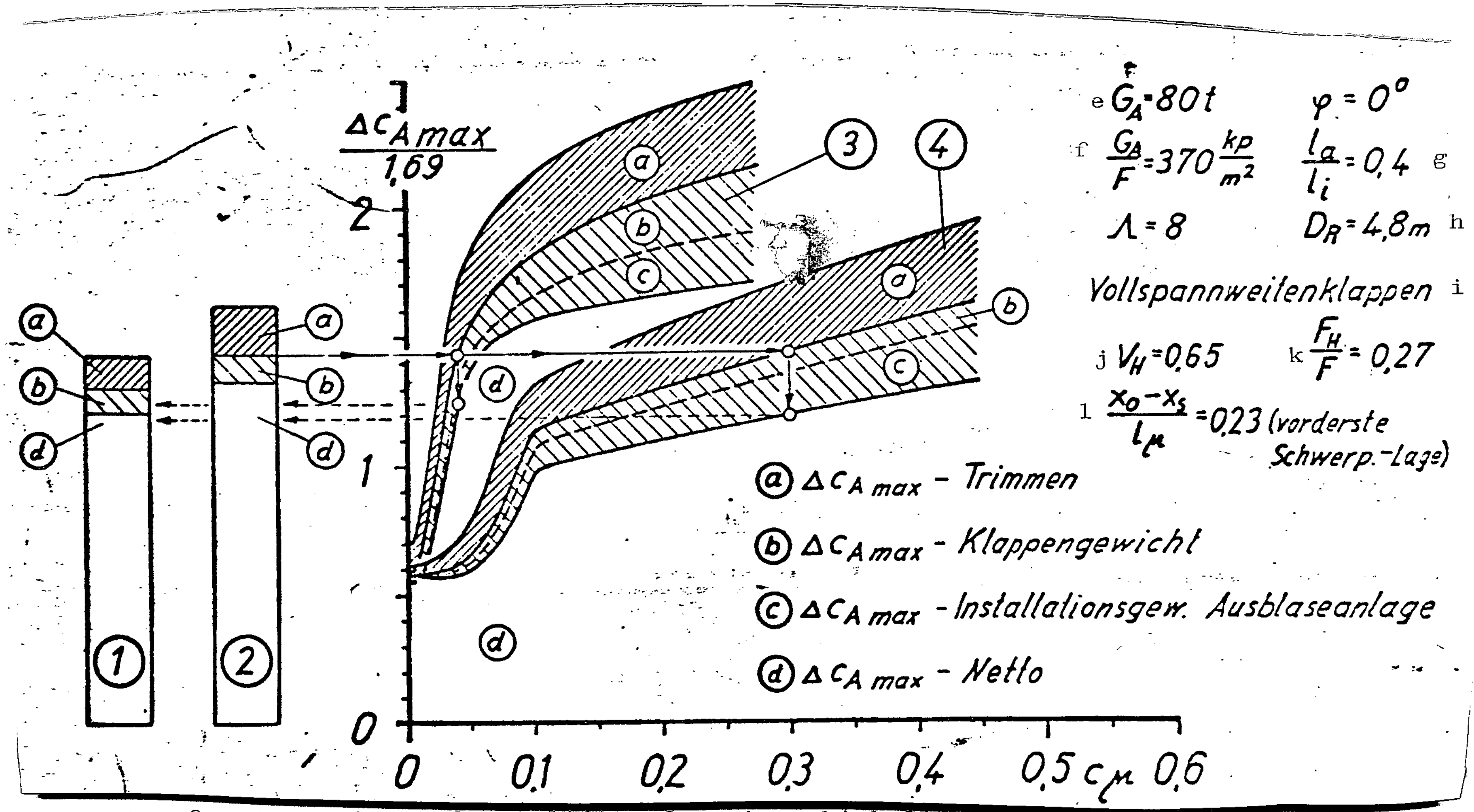

Fig. 8. Comparison of net lifts of various high-lift systems

Key: (1) MBB slat and Fowler flap with split flap; (2) Slat and triple-slotted flap; (3) Nose flap and ONERA double flap; (4) Nose flap and blown plain flap;
$\Delta c_{A\ max} = \Delta c_{L\ max}$
(a) Trimming; (b) Flap weight; (c) Installed weight of augmentation system; (d) Net; e. Takeoff weight; f. Surface load (kg/m^2); g. Wing taper; h. Fuselage diameter; i. Full-span flaps; j. Elevator volume; k. Elevator area/wing area; l. $(x_o - x_{cg})/l_\mu$ = forwardmost center of gravity location

REFERENCES

1. Mavriplis, F., "Aerodynamic research on high-lift systems," AGARD Lectur Series No. 43 on Assessment of Lift Augmentation Devices, 1971. Presented at the von Kármán Institute, Belgium, April 20-24, 1970.

2. Mavriplis, F., "Aerodynamic research on high-lift systems," Canadian Aeronautics and Space Journal, May 1971.

3. van den Berg, "Some notes on two-dimensional high-lift tests in wind-tunnels," AGARD Lecture Series No. 43 on Assessment of Lift Augmentation Devices, 1971. Presented at the von Kármán Institute, Belgium, April 20-24, 1970.

4. Riegels, F. W., Aerodynamische Profile, [Aerodynamic Sections], R. Oldenburg, Munich, 1958.

5. Cahill, F., "Summary of section data on trailing-edge high-lift devices," NACA Report 938, 1949.

6. Abbott, I. H. and von Doenhoff, A. E., Theory of Wing Sections, Dover Publications, Inc., New York, 1959.

7. Amtsberg, J., DLR publication appearing in the near future, with wind tunnel data for triple slotted landing flaps.

8. Schlichting, H. and Truckenbrodt, E., Aerodynamik des Flugzeuges, [Aerodynamics of Aircraft], Vol. 2, Springer-Verlag, Berlin/Göttingen/Heidelberg, 1960.

9. Schulz, R. W., "Considerations involved in developing the Boeing 727," Luftfahrttechnik-Raumfahrttechnik 9 (5) (May 1963).

10. Smith, A. M. O. "Aerodynamics of high-lift airfoil systems," AGARD Conference Preprint No. 102 on Fluid Dynamics of Aircraft Stalling, April 1972.

11. Bartelt, E. and Bielefeldt, E.-A., "Aerodynamic studies on the efficiency of various leading-edge and trailing-edge auxiliary high-lift systems," MBB Report No. UH 8/1-70, unpublished.

12. Poisson-Quinton, Ph., "Some physical considerations concerning blown airfoil systems," WGL 1956 Yearbook.

13. Thomas, F., "Studies on increasing wing-assembly lift by affecting the boundary layer with augmentation," DFL Report No. 174, 1962.

14. Streit, G. and Thomas, F., "Experimental and theoretical studies on blown airfoils and their use in aircraft design," WGLR 1962 Yearbook.

15. Fiecke, D., "The determination of aircraft polars for design purposes," DVL Report No. 15, 1956.

16. Rebuffet, P., "Lift augmentation for a swept-back wing by controlling the boundary layer, making use of turbojet air bleed," excerpt from the proceedings of the International Mechanics Colloquium, Poitiers, 1950, Vol. II.